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GEOLOGY AND ORE DEPOSITS

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Abstract

The plate tectonic concept has had implications for almost all aspects of Earth Science over the past ten years including the distribution and genesis of ore deposits. This has coincided with:

(a) Increased emphasis on the conditions surrounding the formation of the rocks that enclose an ore deposit rather than emphasis on later metallogenic processes.

(b) The increased diversity and sensitivity of geophysical and geochemical methods used in the search for new ore deposits.

The relationships of many metallic deposits to plate boundaries has become increasingly clear, the best example perhaps being that of porphyry copper deposits. Other plate boundary relationships range through various metallic deposits to concentrations of evaporites and petroleum.

The fact that few if any new discoveries can be attributed directly to the application of the plate tectonic concept must be accepted. It has shown convincing reasons why the deposits were there after they have been discovered. The actual discovery has usually resulted from the application of geophysics, geochemistry or conventional prospecting to areas selected by empirical reasoning, e.g. the observed association of porphyry copper deposits with mountain systems bordering the edge of continents. The concept of volcanogenic base metal deposits related to volcanic centres can claim more discovery credit but even here acid lavas were empirically used as favourable indications with success before the present concepts were established.

In future geologists must aim to be more directly constructive in using the plate tectonic concept and its various implications in the concentration on more specific areas for exploration that could not be accurately selected by purely empirical reasoning. This may turn them more towards the search for deeply-penetrating crustal fractures which may not be visible at surface. Such may be forecast by plate tectonic studies and identified by deeply-penetrating geophysical techniques or by broad but sensitive geochemical surveys.

Résumé

La notion de tectonique des plaques est utilisée dans presque tous les domaines des sciences de la terre depuis dix ans y compris l'étude de la répartition et de la genèse des gisements métallifères.

En même temps, on a davantage prêté attention:

(a) aux conditions dans lesquelles se forment les roches encaissantes qu'aux processus métallogéniques ultérieures,

(b) à la diversité et à la sensibilité des méthodes géophysiques et géochimiques utilisées dans la recherche de nouveaux gisements métallifères.

Les relations entre un grand nombre de gisements métallifères et les limites des plaques sont devenues de plus en plus claires, le meilleur exemple étant probablement celui des gisements porphyriques cuprifères. Les autres cas de gîtes liés aux limites de plaques vont des gîtes métallifères aux accumulations d'évaporites et d'hydrocarbures.

Cependant, on doit reconnaître que très peu de découvertes peuvent être attribuées directement à l'application de la notion de tectonique des plaques. Ce concept a davantage démontré, une fois que les gisements ont été découverts, à quoi était due leur présence. Les découvertes actuelles résultent normalement de l'application de la prospection géophysique, géochimique, ou conventionnelle dans des régions choisies par un raisonnement empirique; on a par exemple observé que les gisements porphyriques de cuivre étaient associés aux systèmes montagneux qui bordent les continents. Le concept de l'association de gisements de métaux de base avec des centres volcaniques, a sans doute favorisé un plus grand nombre de découvertes, mais, dans ce cas, aussi, c'est la présence de laves acides qui nous a guidés, avant de faire appel aux notions actuelles.

A l'avenir, les géologues doivent apprendre à utiliser la notion de tectonique des plaques et ses diverses implications, et chercher à explorer plus spécifiquement des secteurs dont le choix ne peut être fait de fa on purement empirique. Ceci pourrait orienter les recherches vers l'exploration des fractures profondes de la croûte terrestre, et qui restent cachées en surface. On peut les déceler par l'étude de la tectonique des plaques, et les identifier par des méthodes d'exploration géophysique à grande profondeur, ou par des levés géochimiques larges, mais très précis.

INTRODUCTION

The principal objective of this symposium volume is to review the state of the art of the application of geophysics and geochemistry to the search for new mineral deposits. By means of the case histories and comparative studies contributed to provide this review the co-ordination of geology, geophysics and geochemistry and the co-operation of those specializing in each should also be improved.

This paper provides a geological framework of the changing concepts that have coincided with the refinements and new techniques in geophysics and geochemistry that will be discussed in the remaining papers presented at the Symposium.

Two major concepts developed over the past decade and a half, the contributions these have made to mineral exploration, but also the limitations in their practical applications, and how these might be overcome in the future are reviewed briefly.

CONTEMPORANEITY OF ORE AND ENCLOSING ROCKS

The first concept deals directly with ore genesis and applies to widely differing groups of metals. Its basic trend, however, has been to relate mineralization more closely to the conditions prevailing at the time of the formation of the enclosing rocks rather than to later geological events. An obvious example is the massive sulphide deposit typified by those of the Noranda area which were once thought to have originated by hydrothermal replacement that took place millions – perhaps hundreds of millions – of year after the volcanic or sedimentary host rock was formed. Today most accept the thesis that the initial deposition of such orebodies was approximately synchronous with the enclosing rocks although recognizing that much later remobilization has played a critical role. In many cases this remobilization has resulted in changing the final grade and mineral form in directions favourable to economic exploitation.

Another example of the basic change in thinking towards contemporaneity of deposition with at least the hanging wall and towards formation at, or close to, the then surface is that of uranium in the so-called "vein class" which I prefer to term the "unconformity class" since the form of the orebodies is only incidentally in fracture fillings. In this case the concept that supergene concentration played at least a major part in the present ore grades has replaced, in the minds of many geologists, the former assumption of much later hydrothermal replacement.

Both examples are typical of the general swing towards accepting contemporaneity between ore and wallrock and towards surface or near surface origin for many metallic deposits. It is a general concept, that has a direct application in the selection of areas for concentrated exploration and it has already contributed significantly to the discovery of individual orebodies. Without any clear understanding of their meaning it is, of course, not always easy to separate sharply the conscious application of the working hypothesis from the empirical use of observed relationships. For instance, long before the volcanogenic origin of Archean sulphide orebodies was suggested many geologists had noticed that such orebodies commonly appeared to have a spatial relationship with acid lavas or pyroclastics. The name "mill rock" was applied by one geologist to the coarse volcanic fragmental that he observed was nearly always within sight or sound of an operating mill. In the exploration field I remember when I was with RioCanex that in 1958 we laid out an airborne EM survey over an area of northern Quebec that was selected partly on the presence of a belt of acid volcanics because we had noticed that copper-zinc mineralization elsewhere had this association. The program resulted in finding a modest orebody that made the Poirier mine. In this case empirical information was used without any specific theory to account for the association. The volcanogenic thesis has since been effectively used in selecting areas for the detailed application of geophysics and geochemistry and it was a program based on this theory, started in New Brunswick, that eventually led Texasgulf to the Kidd Creek orebody in northern Ontario.

PLATE TECTONICS AND METALLOGENY

The second major conceptual change that has influenced mining exploration over the past 15 or 20 years is, of course, that of Plate Tectonics. Early in its development – even in the writings of Wegener, Du Toit and Holmes – the implications of Continental Drift on concentrations of ore or petroleum were noted. But it was not until the modern concept of Plate Tectonics was developed that the significance of the overlapping of crustal plates, i.e. subduction zones, came to be considered in the genesis of orebodies as opposed only to their location relative to continental margins. Here again we were probably using ancient plate margins as a guide to exploration in a purely empirical way. The relationship of orebodies to geochronological boundaries had been noted by various people in the geological or mining exploration field for some years before the present Plate Tectonic concept course. I read a paper, as the Presidential Address to the Society of Economic Geologists in 1960, pointing out that if we had restricted our search in the Canadian Precambrian Shield to within 100 miles of any Archean-Proterozoic boundary we would have found 80 per cent of all the known ore deposits in the Shield. However I was not ingenious enough to come up with a reason for the relationship.

In May 1974, a symposium was sponsored in St. John's, Newfoundland by the Geological and Mineralogical Associations of Canada which resulted in a volume of which Canadian earth scientists generally may be justifiably proud. Edited by David Strong (1976) it contains 32 papers by authorities from Britain, Europe, the United States, South Africa and Australia, as well as from Canada from coast to coast. It is the most comprehensive report to date on the relationship of Plate Tectonics to metallogeny and I believe it will acquire increasing respect in years ahead. Examples of particular interest include contributions by A.H.G. Mitchell on the relation of mineral deposits to subduction margins; A.H. Clarke and Associates from Queen's University describing excellent studies on two selected cross-sections in the Andes and another paper by R.H. Sillitoe of Imperial College, London on the same general region; D.F. Sangster and F.J. Sawkins in separate studies on volcanogenic massive sulphide deposits; Takeo Sato on the Japanese sulphide deposits; T.P. Thayer on mineralization related to ophiolites; P. Laznika on the global distribution of lead deposits; A.Y. Glickson of Australia on Proterozoic structures related to Plate Tectonics; W. Walker on global orogeny/unconformity relationships with ore genesis. There have been, of course, many valuable articles and textbooks published before and since this publication dealing with the same field but for sheer, factual information on a worldwide basis it is doubtful if it can be equalled. Despite this it is a sobering conclusion that I do not know of any significant metallic discovery that can be unequivocally credited to the application of the Plate Tectonics concept. All the articles referred to above, and many others in relevant publications, present impressive data showing the relationships of various types of ore deposits to plate margins, etc. and may explain the reasons for their presence. The actual discoveries, however, mainly by drilling on geochemical or geophysical anomalies, have been in areas selected by empirical reasoning. A few examples follow.

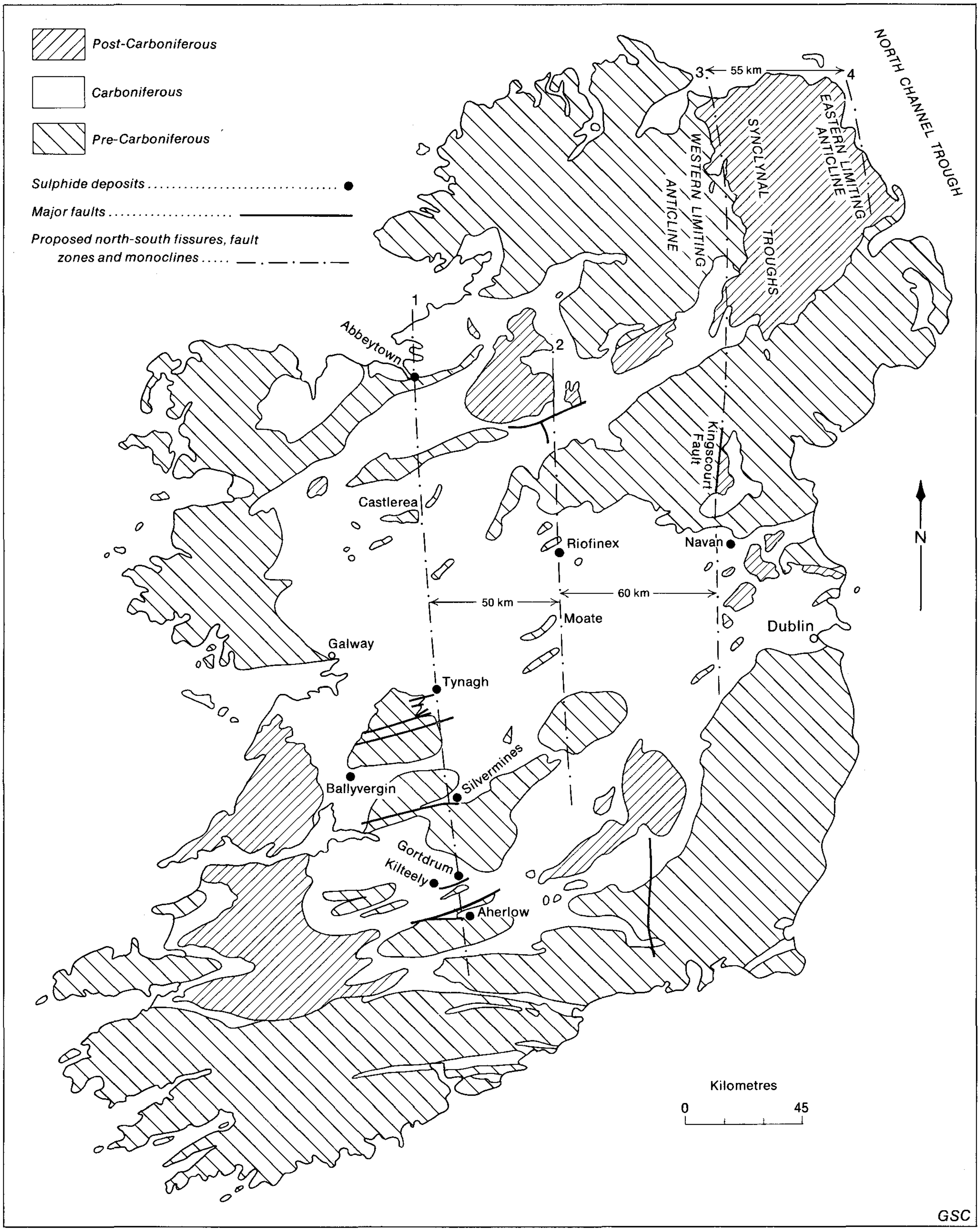

Figure 1.1. Geology of Ireland with postulated north-south geofractures and the larger copper-lead-zinc-deposits in Dinantian (lower Carboniferous) rocks (after Russell, 1968).

Contents

The most consistent relationship with plate margins is that of porphyry copper deposits with subduction zones. But many years before the present concept of Plate Tectonics, the pattern of porphyry coppers paralleling the trace of continental margin orogenies had been noted and used in long-term exploration strategies by major base metal companies. Such empirical reasoning indicated favourable zones measurable in thousands of linear kilometres. I do not believe, much as I would like to, that the admirable and formidable accumulation of research as summarized in the GAC Volume referred to above has really enabled us to concentrate our efforts in, say, 15 or 20 per cent of the linear extent of a potential porphyry copper belt over a subduction zone while eliminating the rest as being relatively unfavourable. Much the same must be said for the relationship of Plate Tectonics to lead/zinc deposits which tend to form belts parallel to the porphyry coppers but farther from the plate margins – we can explain the controls logically but can we apply the knowledge or theory, with any conviction, in the selection of areas on which to concentrate our exploration expenditures and geochemical or geophysical tools? Our selection of areas is still largely empirical based on observations of petrological or sedimentological associations.

The recognition of ophiolites as material originating from the ocean floor was of particular importance in the development of the Plate Tectonics concept. Linear zones of discontinuous ophiolite occurrences are probably the most reliable indicators of sutures marking the lines of collision between tectonic plates, e.g. the Tseng-Po – Indus valleys line in Asia, marks a major, if not the main, line of impact of the Indian and Eurasian plates. More recent studies in Newfoundland have identified ophiolites as indicating the sutures of former plate collisions in Appalachian-Caledonian times.

From the economic standpoint the studies of the Cyprus pyrite and copper deposits in ophiolites by Hutchinson (1965) and others, which led to conclusions of a dominantly syngenetic rather than replacement origin, predated the general acceptance of the Plate Tectonic concept. The more recent discovery, or rather re-discovery of deposits worked between 500 and 2500 years ago, in the most extensive ophiolite area in the world, the Sultanate of Oman, was made by Charles Huston of Toronto and his associates, not on the basis of Plate Tectonic reasoning but as the result of reading a book on the archaeology of the area and following this with geological and geophysical reconnaissance which defined drilling targets (Crone, 1979).

Substantial reserves of chromite are known in ophiolites in various parts of the world and there is no doubt that future searches for this strategic metal will be concentrated in ophiolite zones already known and, possibly, in some not yet known which may be found as a result of Plate Tectonic reasoning. Up to the present (1977), however, it is questionable if any new production or substantial reserves can be credited directly to Plate Tectonic reasoning.

The Kuroko and related deposits of Japan have been restudied by many Japanese geologists in the light of Plate Tectonic concepts and the relationship of this type of deposit to island arc stages of plate boundaries has been convincingly demonstrated. As far as I am aware, however, any new discoveries made of this type of deposit have been the result of drilling based on detailed studies of the volcanic stratigraphy and the configuration of the underlying basement, followed by the application of various geophysical techniques, and cannot be attributed even indirectly to Plate Tectonic reasoning. Nevertheless such reasoning may instigate new exploration in the volcanic sequences of other island arcs such as the North Island of New Zealand and other parts of the South Pacific.

I have mentioned a few types of deposits that seem to have particularly close relationships with Plate Tectonics. However it is difficult to show convincing evidence that the acceptance of these principles has directly aided exploration. It is to be hoped that the next stage of study and increased knowledge in the Plate Tectonics field may bring out new concepts or working hypotheses that could help concentrate exploration efforts more precisely than on, for example, the general trend of plate boundaries. The following are merely speculations in the directions these might take.

Metallographic Selection

The concept, or perhaps more correctly the observation, of metallographic areas long predates Plate Tectonics and was discussed by de Launay in the first quarter of this century. Nevertheless it is still almost as much a mystery as it was 75 years ago why certain areas of the world seemed to produce an anomalous number of deposits of a particular metal or association of metals spread over several geological events. Perhaps tin is the most intriguing and frustrating in that about 59 per cent of the world's known reserves of this metal (from Commodity Data Summaries, 1977) are in an area, including Thailand, Malaysia, western Indonesia and the southwest part of the Peoples Republic of China, amounting to about 3 million km^2 or less than 0.6 per cent of the world's surface. This tin mineralization, moreover, is associated with granites intruded in at least three periods between 300 and 48 million years ago. An additional 12 per cent of global tin reserves are in a relatively small area of Bolivia and are distributed over at least four orogenic periods, the last of which (about 20 million years ago but extending up to a million years or so ago) is responsible for the largest proportion. Both the Far Eastern and the Andean examples are within plate boundary zones but occupy a frustratingly small proportion of their extent. If we could understand the reasons for these two concentrations we might be able to apply the knowledge to finding new tin metallographic areas (probably smaller than the two mentioned) which would reduce our concern on future global supplies of what is probably the most critical of all base metals.

A highly respected geologist and author, Pierre Routhier (1976), has presented some thoughts on metallographic zones. His suggested relationships of tin areas of the world are, to me, unconvincing but some of his more positive observations in central and southern Europe, in which he is an acknowledged authority, are of considerable interest. He points, for example, to the broad belt of mineralization that contains the famous Rio Tinto mines in Spain. He noted that, within this easterly-trending belt of Paleozoic sediments and volcanics, zones of copper and pyrite mineralization alternate with those of manganese and lie at an oblique angle to the mineralized belt as a whole. He also pointed to belts of lead-zinc mineralization in western Europe that cut across geological boundaries and include deposits of varying ages and type (Routhier, 1976). The first of these extends from the Ardennes (Belgium) to Upper Harz (West Germany) and contains metallic deposits dating from mid-Devonian to Triassic including both vein fillings and tabular-bedded bodies. A second belt, less firmly established, extends from the north of Spain in a northeasterly direction across the Pyrennees and along the southern edge of the Alps. This also includes deposits that seem to disregard age boundaries and types of deposits but the dominant metals are lead and zinc. It should be noted that the Trepca deposits in Yugoslavia, the most important source of lead and zinc in continental Europe, are not within either of the above zones but may fall into a separate, less extensive one.

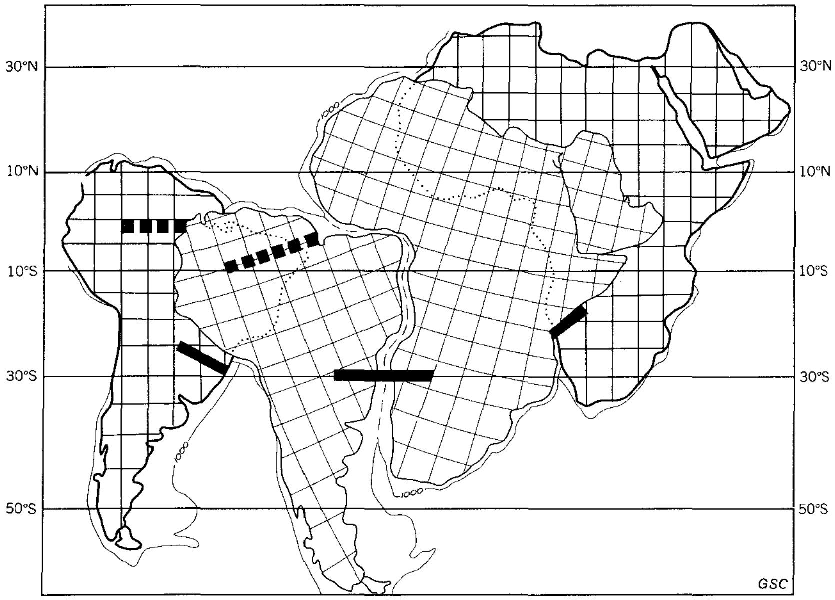

Figure 1.2. *Orientation of geofractures in Africa and South America pre- and post-continental drifting (after Kutina, 1976).*

Routhier 1976 also drew attention to a belt of predominantly copper deposits, some being significant producers and others of mainly scientific interest, that extends in an arc-shape oriented roughly north-south for 550 km through Bulgaria, eastern Yugoslavia and Romania in host rocks varying from Upper Mesozoic to mid-Tertiary age.

What is the controlling feature in each of these examples? No observable fracture zones exist coinciding with the metallographic belts but one is driven towards the conclusion that some crustal fracture systems predating present host rocks must exist. Routhier reached no definite conclusion but considered that "the Zn-Pb belts can, therefore, be considered as revealing former structural directions partly hidden by more recent phenomena". He continued further "that is the fundamental question: were the metallogenic provinces grafted on to the pre-formed geochemical provinces, and how?"

Primordial Crustal Fractures

The concern with fractures, invisible at the surface, that individually seem to coincide with several ore deposits or occurrences on separate structural belts, has occupied the minds of geologists in several parts of the world. E.A. Noble has studied these phenomena for many years and speculated on their origin. E.B. Brock, working mainly in South Africa but applying his ideas to global tectonics generally, included the relationship of crustal fractures to concentrations of mineral deposits.

One approach to the possible significance of cross-cutting "geofractures" that cannot be recognized on surface is that of Russell (1968) studying especially the lead-zinc deposits in Ireland (Fig. 1.2) and also those in parts of Britain and Greenland. He pointed to the fact that of twelve deposits in Ireland, each containing over 10 000 tons of lead-zinc (or the equivalent value in other metals), five lie on a line trending 8° west of north, these being Abbeytown, Tynagh, Silvermines, Gortdrum and Aherlow (the last two copper-silver mineralization). Russell postulated other north-south geofractures at roughly equidistant intervals of between 45 and 65 km. It may be noted that the biggest zinc-lead deposit at Navan cannot be "matched" on a north-south line with any other known deposits, although it is on a line passing through the Kingscourt inlier in an expected, roughly equidistant position.

I.S. Thompson, who worked with me in Ireland some years ago, independently noted the roughly equidistant north-south "lines" on which mineral concentrations appeared to lie. These observations were not published, for reasons of exploration strategy, but were used empirically in the selection of areas for geochemical programs with some encouraging results although not as yet of economic significance.

Russell (1976) suggested that these vertical zones of weakness formed in the upper crust are a result of east-west relative tension and high pore fluid pressures. These may have permitted hot waters that were freed at depth and migrated towards tensile stress concentrations at the bottom of the geofractures there to be transferred towards surface by convection flow carrying metals leached from geosynclinal rocks. Where there is adequate sulphur, the metals are precipitated over the intersections of the geofractures with crosscutting favourable structures – in this case mainly normal faults trending east-northeasterly.

The primary cause of such geofractures, if they exist, is a matter of speculation but Russell has suggested that they might be related to the initiation of the major fracture that resulted in the mid-Atlantic ridge.

Another writer who has been impressed with the influence of crosscutting, and sometimes equidistant fractures and veins, is J. Kutina. His first studies were in the Bohemian Massif in Czechoslovakia but subsequently in other parts of the world including North and South America. In western Czechoslovakia he showed the roughly equidistant pattern of north-south faults and vein systems that crosscut the boundaries of age and structural units. In a more recent paper Kutina (1976), compared the source of patterns shown in Kutina (1968) with the spacing of fracture zones of deep ocean floors and suggested a possible relationship between mineralization and "hot spots" in the mantle such as proposed by Sillitoe (1974).

Kutina pointed out that geofractures that extended across the boundary of two formerly-joined continents do not necessarily have common orientation today (Fig. 1.2). For example, it is known that Africa, when it was attached to South America over 140 Ma ago, had its long axis tilted in a southwesterly direction 30° from its present north-south one. Similarly South America had its present north-south axis tilted 15° in a southeasterly direction. Accordingly if an east-west fracture system crossed the boundary prior to the parting of the continents the two halves of the fracture system would now differ in orientation by 45°.

Observations on deep and ancient structures that may have influenced metallogenesis have been made by a number of writers in the U.S.S.R. including Favorskaya (1976) who attempted to correlate the metallogenic generalizations resulting from Plate Tectonic concepts with the observed regularities in the distribution of large deposits when considering them as major geochemical anomalies. The depth of the lineaments is shown by their through-going character, cutting across not only boundaries of different crustal structures but also the boundaries of continents and oceans. The conclusion reached is that these ore-concentrating structures are remarkable for their longevity and variety of sources and are "apparently connected with deeper processes than those that occur at the boundaries of plates".

DISCUSSION

The difficulty with the above observations and speculative conclusions is just that – they are speculative. On small-scale maps it is rather easy to start drawing lines that appear to go through a number of deposits. If, however, on closer and more detailed study the conclusions are found to be too highly based on small-scale assumptions there is a tendency for the earth science fraternity to discard the whole idea. Geophysicists tend to give particularly short shrift to such ideas, finding little if any physical evidence to support them. However geophysicists, who justifiably can claim the major role in the development of the Plate Tectonics concept, should remember, as an exercise in humility, that the fiercest opposition to the ideas of Wegener, Du Toit and Holmes came from geophysicists who claimed that the movement of continents in any form was physically and mathematically impossible. Geologists, a fair proportion of whom (including the writer) must be classified as mathematical morons, accepted such informed criticism rather too easily.

I would suggest that a greater concentration of effort is justified in assembling the evidence of such "geofractures" that may be associated with metallographic belts or alignments of mineral concentrations on a succession of parallel structural belts. The next stage would be to find methods for identifying such geofractures or fracture systems not visible at the Earth's surface by means of seismic or other geophysical applications. I suggest that this is the biggest challenge for geophysicists concerned with mineral deposits and one that should logically be undertaken by government. There are some arguments, in a free enterprise system, against governments carrying out surveys that may specifically pinpoint mineral deposits since this would or could be done by industry at no direct cost to the taxpayer. The sort of project suggested here, however, could only be done properly by a central co-ordinating agency.

In addition to any geophysical approach, since any such fracture systems by their very nature are assumed to extend to a great depth and, perhaps to the mantle, they should be identifiable by means of broad regional geochemical surveys. In this regard the Russian experience should be particularly valuable since the Ministry of Geology of the U.S.S.R. has for many years been carrying out geochemical surveys in mineral exploration over vast areas. This line of research in our own country, and elsewhere where mineral exploration might be carried out, should logically be done by government organizations or by government sponsorship so that the results could be co-ordinated by a single agency.

CONCLUSIONS

I don't want to leave with you the impression that I am denigrating the fundamental relationships between ore genesis and Plate Tectonics. Far from it. I think we will find increasingly close controls as we learn more about the history and processes involved. What I am saying is that there has been a tendency, particularly in papers written for non-specialist earth scientists or for those in other sciences, to give the impression that a new tool has been presented to the exploration geoscientist that has fundamentally changed and simplified his task in the selection of areas. This is not yet the case. Most recent successful exploration for any minerals, whether metals, non-metals or petroleum, has been in areas selected empirically on the basis of observed geological or geographical relationships which fit well into the Plate Tectonic concept but were not directly derived from it. As we learn more of the detailed tectonic mechanisms involved I believe we will be able to use greater precision in the selection of areas for exploration. The identification of the more detailed structures and mechanisms of plate movement will depend heavily on regional geophysics and geochemistry and the resulting follow-up programs will require still greater penetration and sensitivity in defining drilling targets.

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